

NEW EXCITATION SIGNALS FOR AIRCRAFT GROUND VIBRATION TESTING

S. Giclais¹, P. Lubrina¹, C. Stéphan¹, M. Böswald², Y. Govers², J. Ufer², N. Botargues³

¹ ONERA
29, avenue de la Division Leclerc
92320 Châtillon
France

² DLR – German Aerospace Center - Institute of Aeroelasticity
Bunsenstrasse 10
37073 Göttingen
Germany

³ AIRBUS Operation SAS – EGLAV
316 route de bayonne, BP M0132/2
31060 Toulouse Cedex 03
France

Keywords: Ground Vibration Testing (GVT), Modal Identification, Excitation Signals

Abstract: For the last 12 years, DLR and ONERA are involved in the realization of the Ground Vibration Testing (GVT) campaigns for AIRBUS civil aircrafts. Continuous developments are carried out in order to improve the test productivity without jeopardizing the quality of the experimental database deliveries, especially in the case of non-linear structural behaviors. Among the recent developments, DLR and ONERA are suggesting new excitation stimuli, such as multi-sine sweeps and low crest factor random signals. These signals have been tested during a research GVT campaign in March and April 2011, on an A340-600 aircraft. This paper is devoted to assessing the relevance of these new signals within an industrial context.

1 INTRODUCTION

Measuring key structural properties (eigenfrequencies, mode shapes, generalized mass & damping, transfer function, non linearity) the Ground Vibration Test is an indispensable milestone in the aircraft development process.

The test planned on first prototype of new aircraft, allows calibrating global dynamic finite element model (several hundred thousand degree of freedom) removing uncertainties, which could lead to poor prediction. It is also the only reliable way to measure structural damping. Damping as a major driver of the aircraft response under any dynamic excitation is a key not-to-miss parameter. The adjusted structural model (mass, stiffness and damping) feeds afterwards theoretical simulations of the overall engineering community: aeroelastics, flight and ground loads, comfort, dynamic qualification of major systems and structures.

The GVT is an essential support of the flight test campaign, ensuring the first flight safety and supporting fast flight domain opening. It is also used as a mean of compliance in front of Airworthiness Authorities during the aircraft certification.

1.1 Industrial Context

Placed just before the first flight on a representative structure of the in-flight aircraft, the GVT is on a very critical path of the final aircraft assembly. Despite the test stakes, the timeslot is highly pressurized to fit with the challenged program timelines with the pre-requisite not to jeopardize the measurement quality obtained with former methods that is the reference for safety.

On top of these constraints, more aircraft configurations (mass cases, landing gears, high lift ...), more eigenmodes (top end loads and aeroelastic simulations rely on enhanced modal basis) must be addressed from an minimum set of excitations configurations. Excitation strategy must be heavily optimized.

Excitation strategy must also cope with innovative structures (new materials, new assembly) and non-linearities (backlashes, frictions, soft mounts...). Within a minimum number of attempts a wide amplitude of excitation forces has to be tested (up to levels as close as possible to real aircraft solicitations). Reliable impedance curves characterizing the non-linear evolution of the dynamic parameters versus the excitation amplitude are an essential outcome of the GVT.

1.2 Excitation Strategy

Nowadays, the “state of art” of large aircraft Ground Vibration Testing using Phase Separation Methods (PSM) is based on swept-sine excitation signals applied simultaneously on two shakers. The disadvantage of such a process is the duration of the test, due to the number of sweeps to perform (symmetric and anti-symmetric excitation configurations, necessary to improve the conditioning of the input matrix for FRF calculation [1]), and especially when multiple runs at different excitation levels are necessary to detect non-linearities in the structure.

The usage of swept sine excitation often requires a priori knowledge about the dynamic behaviour of the structure. For example, large vibration amplitudes can be generated when sweeping through a resonance of a lightly damped mode that is well excited by the excitation setup. These conditions can be harmful to the vibration exciters that have limited coil stroke and which might run into their mechanical limits. If such an event occurs, in the best case the respective excitation run must be repeated, in a more severe case the vibration exciter is damaged, and in the worst case the test structure might be damaged.

Based on our experience in GVT, and on our observations during previous tests, the idea to define a new kind of excitation signal, based on a combination of multiple swept sine signals running simultaneously appeared. Other “exotic” excitation signals forms like low crest factor random signals have been also investigated.

The use of new excitation signals has the potential to further reduce the testing time in a GVT. In a challenged timeframe, new excitation signals are faced with the following requirements:

- improve the productivity of GVT in a sense that more aircraft configurations and more eigenmodes are addressed within the same short timeframe of a GVT
- keep at least the same measurements quality in comparison with “classical” excitation signals.
- guarantee high excitation force levels at the first attempt

- deal with innovative structures with new materials, new assembly process and associated non-linearities.
- shorter signals at fewer optimized excitation points must be suited to provide a proper knowledge of aircraft dynamics at the end of the test campaign
- non-linearities have to be assessed/investigated and characterized by impedance curves as close as possible of the real aircraft solicitations.

We took profit a recent research GVT campaign, performed in March and April 2011 at AIRBUS Toulouse on an A340-600 aircraft, to apply different types of these new excitation signals and evaluate their impact on the test productivity in a “real” industrial context, and by analyzing the results obtained, estimate their benefits in terms of non-linearities detection and deliveries quality.



Figure 1: Research Ground Vibration Test recently performed on an A340-600

2 TYPICAL EXCITATION SIGNALS USED UP TO DAY IN A/C GVT

The first method (and the oldest) used historically is the method known as "Normal Mode Testing" or "Appropriation". It seeks to establish vibration in a pure mode of vibration by careful selection of the locations and magnitudes of a set of sinusoidal excitation forces. As this method is really time consuming, it is now more and more only applied on few critical modes. For the major part of the other modes, step sine, sweep sine and random excitations were more often used.

Modified versions of the Normal Mode Testing are provided by Multi-Phase Step Sine and Multi-Phase Sweep Sine methods which are also a steady-state sinusoidal type of test. They are faster to use than appropriation methods, but due to the fact that multi-point correlated signals are applied, it needs at least as many runs as there are simultaneous forces applied and the individual force vectors are linearly independent of each other for each run.

Uncorrelated random excitations which are applied simultaneously at different points are one of the typical excitation signals used. Their advantage is that they are fast to use because the complete frequency range of interest is covered immediately, and in comparison with step sine and sweep sine methods, only one run is necessary for FRFs calculation. Their main

disadvantage is that we cannot control with precision the force applied at each frequency, and peak levels can overload exciters when a high level signal needs to be applied.

It was the objective of a research GVT campaign to develop and to validate new concepts in FRF measurements that are in line with the objectives mentioned above. Different approaches have been performed on the improvement of swept sine excitation and crest optimized periodic random excitation.

3 SWEPT SINE COMBINATIONS

3.1 Numerical applications

The proposed methodology is firstly applied on simulated signals in order to prove its relevancy. Accelerations of some degrees of freedom due to arbitrary excitation forces can be calculated thanks to a state model as:

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx\end{aligned}\tag{1}$$

with $x = [q^T \quad \dot{q}^T]^T$ the state vector and q the modal response vector. A is the state matrix, B the controllability matrix, C the observability matrix are based on modal data [2]. In this application, conservative modes are computed by an updated FE model of the structure. As no damping is available in the FE model, values of modal damping are randomly chosen in the range 0.5-4 %.

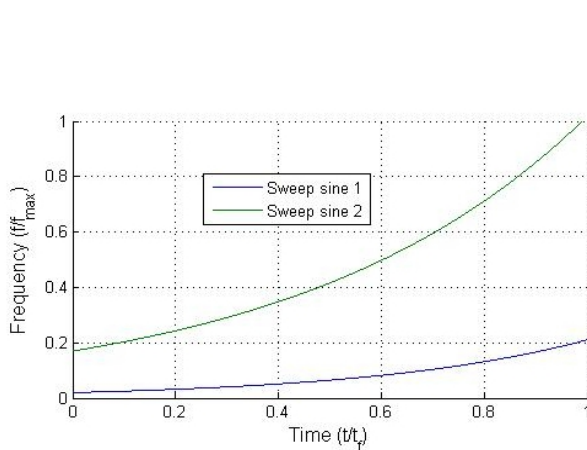


Figure 2: Frequencies evolution of the combined sweep sine case

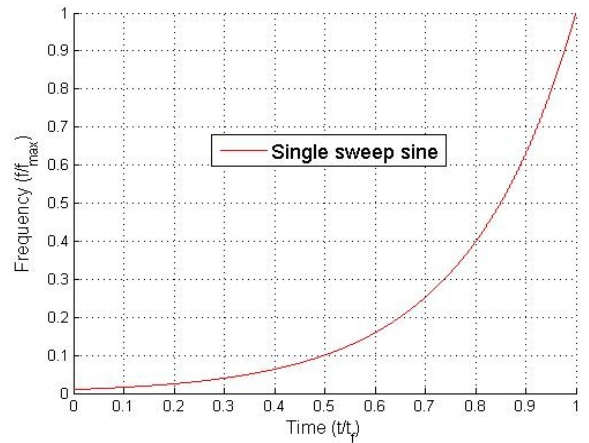


Figure 3: Frequencies evolution of the single sweep sine case

In this part, two cases of excitation patterns are considered. The first one is a combination of two sweep sines (see figure 2). One sweep sine is devoted to low frequencies and the other one to high frequencies. It is a symmetric excitation on the outer engines for both sweep sines. Each sweep sine has its own speed rate in order to complete together.

FRFs computed from this excitation pattern will be compared to the single sweep sine case which covers the low and the high frequency ranges (see figure 3). It is a classical excitation signal and is considered here as the reference.

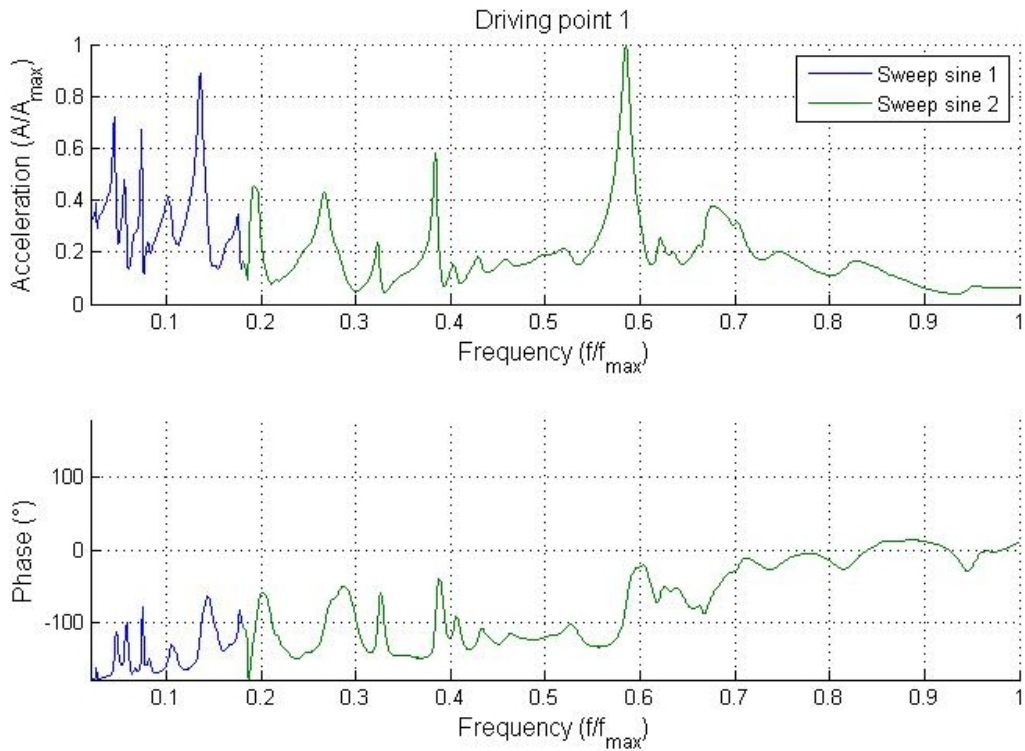


Figure 4: FRF of the driving point 1 for the combined sweep sines case

On figure 4, FRF of the first driving point is depicted. It can be noticed that, although the speed rates of both sweep sines are different; there is a good continuity between the left and the right parts of the FRF.

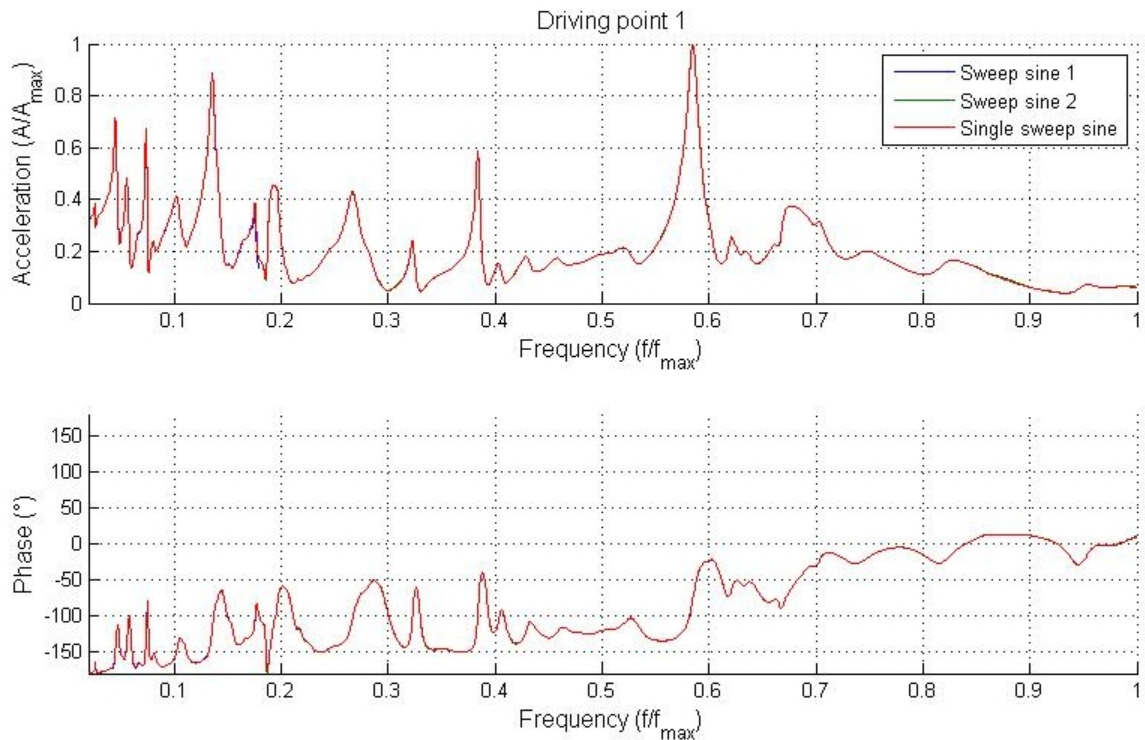


Figure 5: Comparison of the combined sweep sines case with the single sweep sine case

On figure 5, FRFs of the driving point 1 are depicted for both cases of excitation. Curves are almost indistinguishable. FRFs obtained from a combined sweep sines excitation force are equivalent to them obtained by a single sweep sine excitation force. Then it confirms that the proposed process is relevant on a numerical case.

3.2 Experimental applications

We have tested different kinds of sweep sine combinations during the GVT campaign. The idea was to confirm the results obtained numerically on a “real” structure, with different objectives in each case.

Case I:

Decomposition of the frequency range of a single sweep sine in a combination of two sweep sine signals running simultaneously in sub-frequency ranges (the complete frequency range covered stays the same). The principal objective was to reduce the duration of the acquisition run.

We have performed two runs, one with a symmetric excitation and the other one with an anti-symmetric excitation on the outer engines in Z (figure 6).

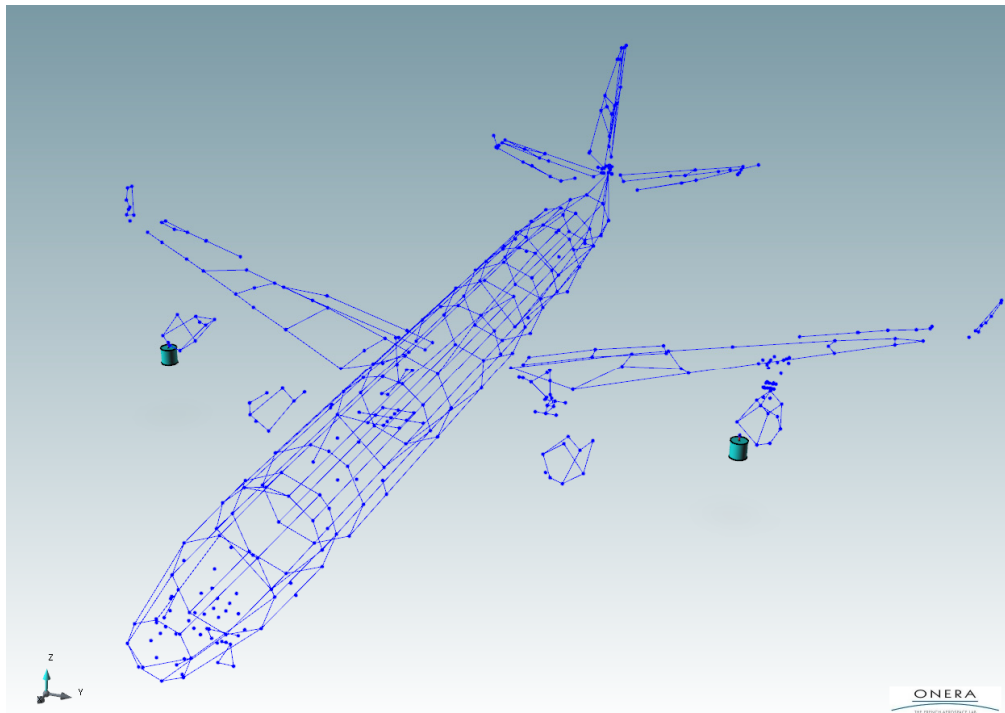


Figure 6: Location of the exciters on the A/C - Excitation on both outer engines in Z

Figure 7 shows the combination of sine sweeps applied. The sweep speed was adapted to cover the two sub-frequency ranges in the same time. In comparison with a unique sweep covering the complete frequency range, we have reduced the acquisition time by two.



Figure 7: Sweep sine combination to cover frequency range f1-f2'

Conventional method for FRF estimation (by inverting the input matrix) implies uncorrelated excitation signals. In this case, for correlated multi-points excitations, instead of computing the FRFs as MIMO from the combination of the measurements issued from symmetric and anti-symmetric excitations, the concept of the virtual single driving point (SVDP) processing, which allows the use of the existing SIMO processing, was used [1],[3]:

$$P(\omega) = F_V \times \dot{X}_V = \sum_{exciters} F_e \times \dot{X}_e \quad (2)$$

- $P(\omega)$: Complex Power
- F_V : Virtual single constant force
- \dot{X}_V : Velocity response of the virtual driving point
- F_e : Actual excitation force acting at the driving point e
- \dot{X}_e : Velocity response of the actual driving point e

The results obtained with the SVDP processing for the symmetric excitation (figure 8) are coherent with the ones obtained numerically. There is an excellent continuity between the two FRFs (one between f1 and f2 and the other one between f1' and f2').

The same processing has been performed on the anti-symmetric run, and the comparison of the results obtained with the symmetric and anti-symmetric excitation (figure 9) allows to distinguish the symmetrical and anti-symmetrical structural modes, which is a welcome benefit in case of high modal density as long as the modes are not asymmetric.

To summarize, the biggest advantage of that kind of combination is the capability to reduce significantly the duration of the run in comparison with a single sweep sine along all the frequency range of interest. Depending of the speed of the sweeps, and the sub-ranges limits, we were able to divide this duration by two. The second advantage is the capability to separate the symmetrical and anti-symmetrical structural modes, and to facilitate the modal identification process.

The only limitation comes from the exciters limits, in term of maximum force (F_{max}) and maximum coil course, which cannot be exceeded. The total force applied ($2 \times F$) cannot exceed F_{max} .

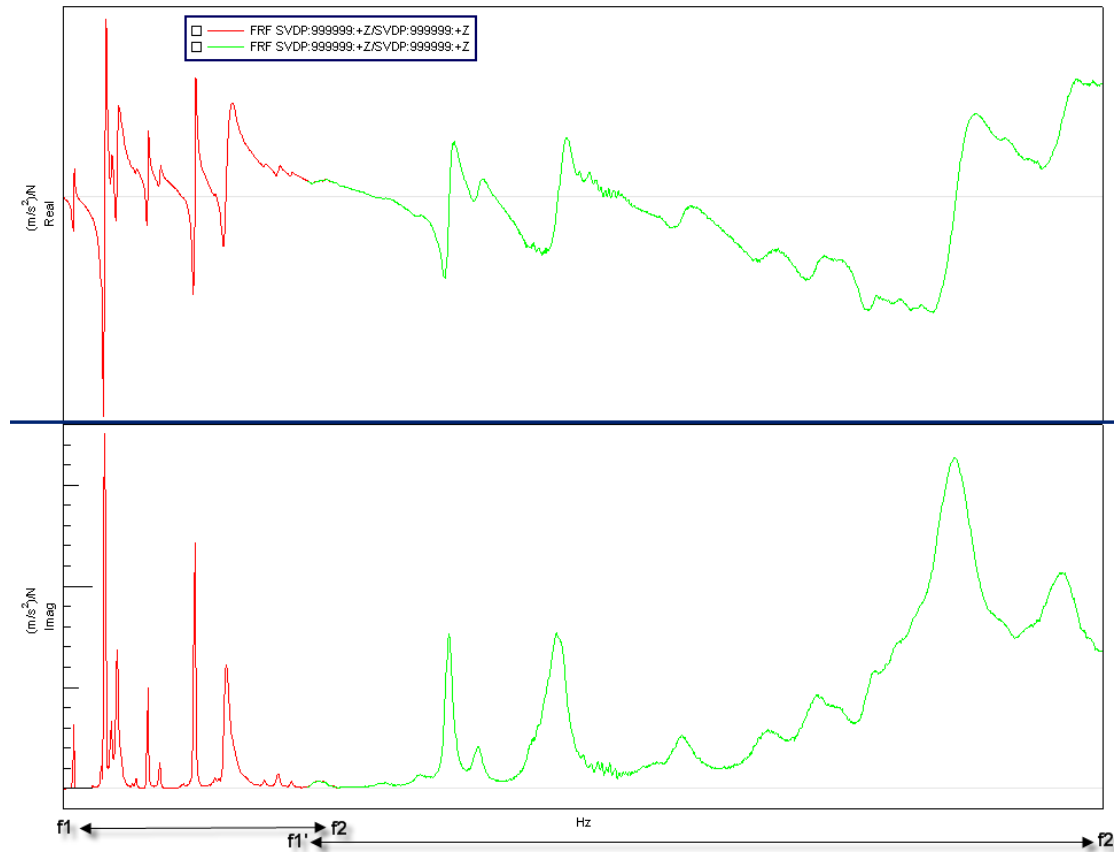


Figure 8: FRFs of the virtual driving point for each sweep sine of the combination for the symmetric excitation

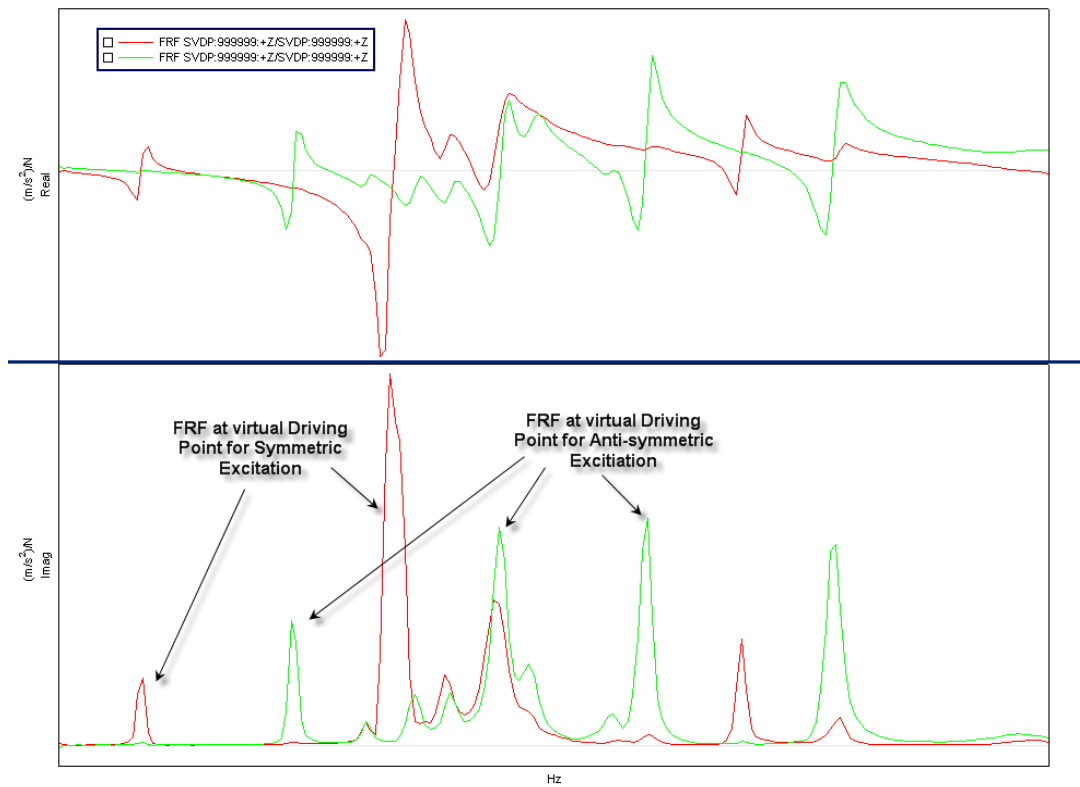


Figure 9: Comparison of FRFs of the virtual driving point for the symmetric and the anti-symmetric excitations

Case II:

Cover the same frequency range with two different levels of force. The principal objective was to detect non linearities and to have, in the same run, at least two different sets of information (frequency, damping and energy applied) for different modes to build quicker their corresponding impedance curves.

We have performed two runs, one with a symmetric excitation and the other one with an anti-symmetric excitation on the outer engines in Y (figure 10).

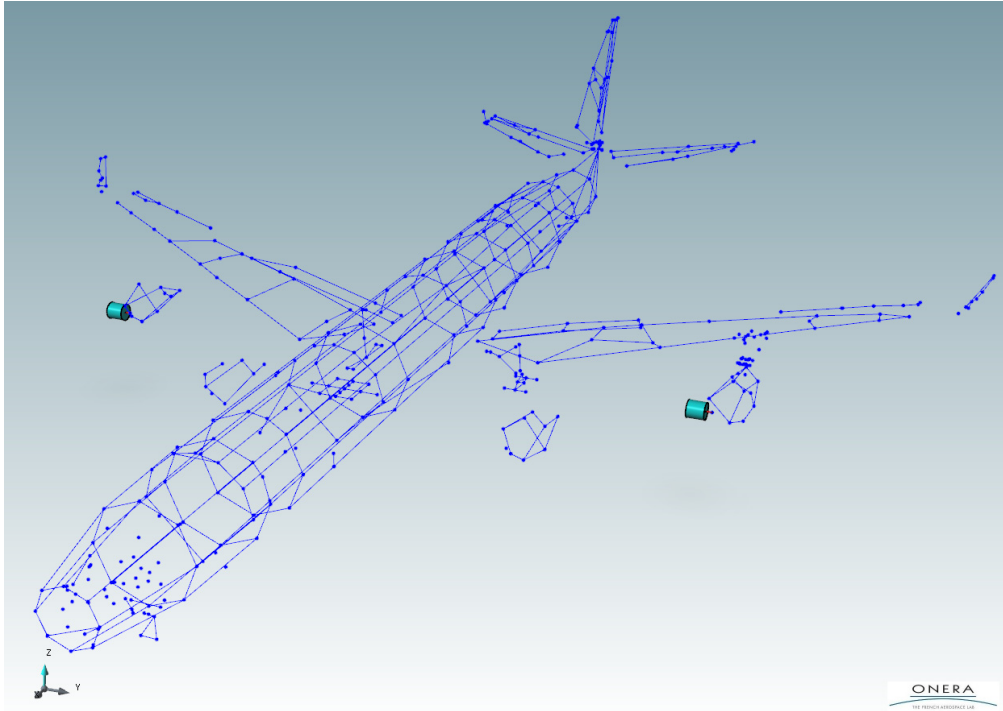


Figure 10: Location of the exciters on the A/C - Excitation on both outer engines in Y

Figure 11 shows the combination of sine sweeps applied. The sweep speed was the same, the frequency range also. The only different was the forces applied. A time delay for the start up of the second sweep was applied because as each frequency was excited two times, we have to be sure that no interference between them will alter the quality of the SVDP processing results.

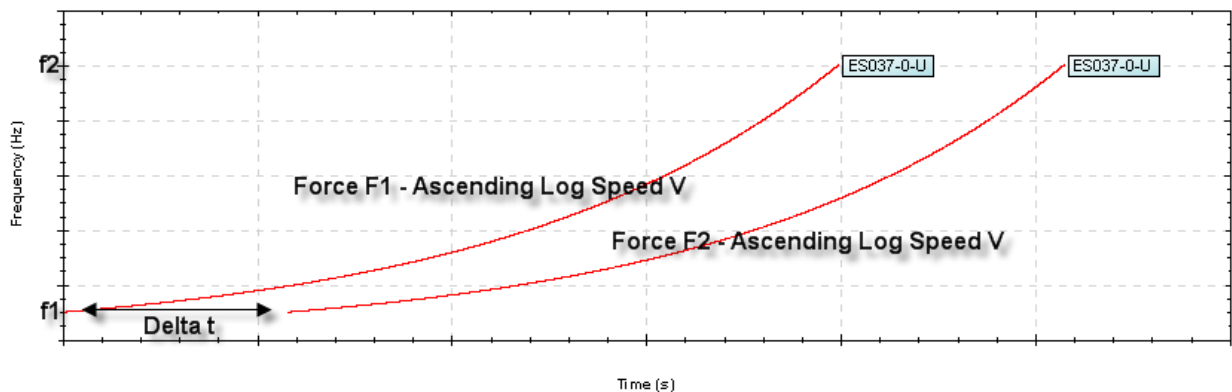


Figure 11: Sweep sine combination to cover frequency range f1-f2 with two different levels of force (F1 and F2)

The results obtained with the SVDP processing for the symmetric excitation (figure 12) exhibit non-linear behaviours. As complex power is also calculated during the SVDP processing, one run was able to give use two sets of information for the impedance curves build up.

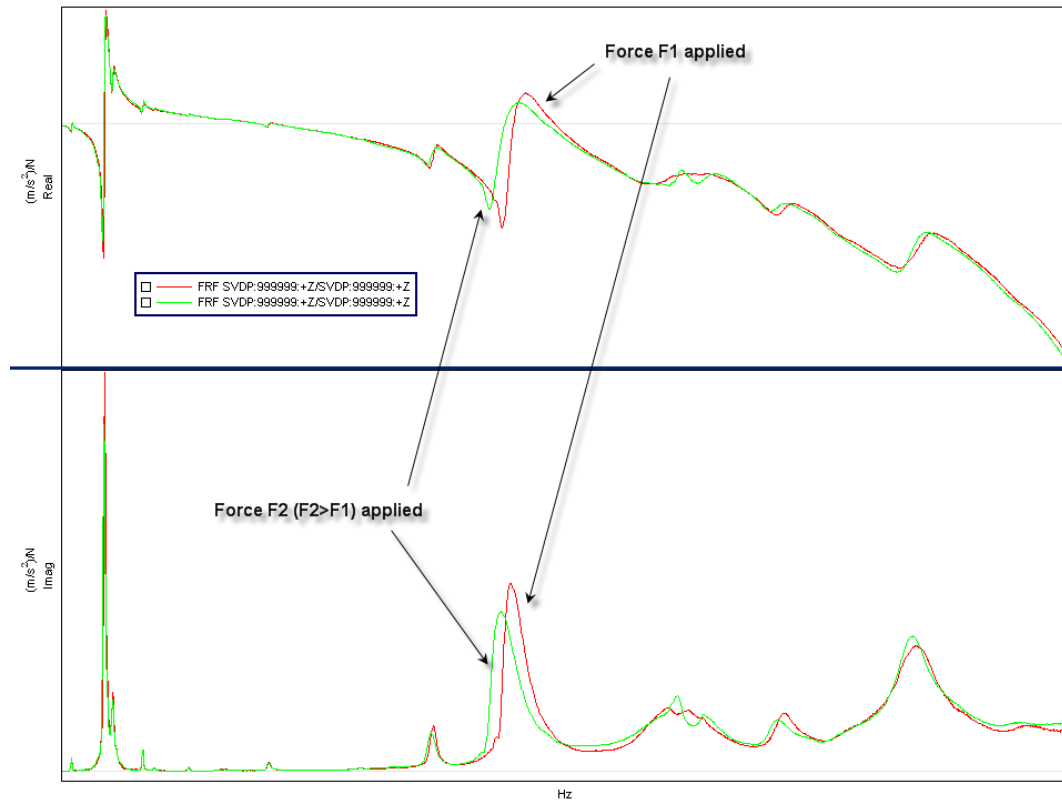


Figure 12: FRFs of the virtual driving point for each sweep sine of the combination for the symmetric excitation

To summarize, the biggest advantage of that kind of combination is the capability to detect non linearities and to reduce (at least by two) the number of necessary runs to build impedance curves. The second advantage is still the capability to separate the symmetrical and anti-symmetrical structural modes, and to facilitate the modal identification process.

The only limitation still comes from the excitors limits, in term of maximum force (F_{max}) and maximum coil course, which cannot be exceeded. The total force applied ($F1 + F2$) cannot exceed F_{max} .

Case III:

Apply uncorrelated sweep sine combinations. The principal objective was to check if computing the FRFs as MIMO gave good results, and to confront them with the virtual single driving point (SVDP) processing ones.

We have performed one run on the elevators in Z (figure 13).

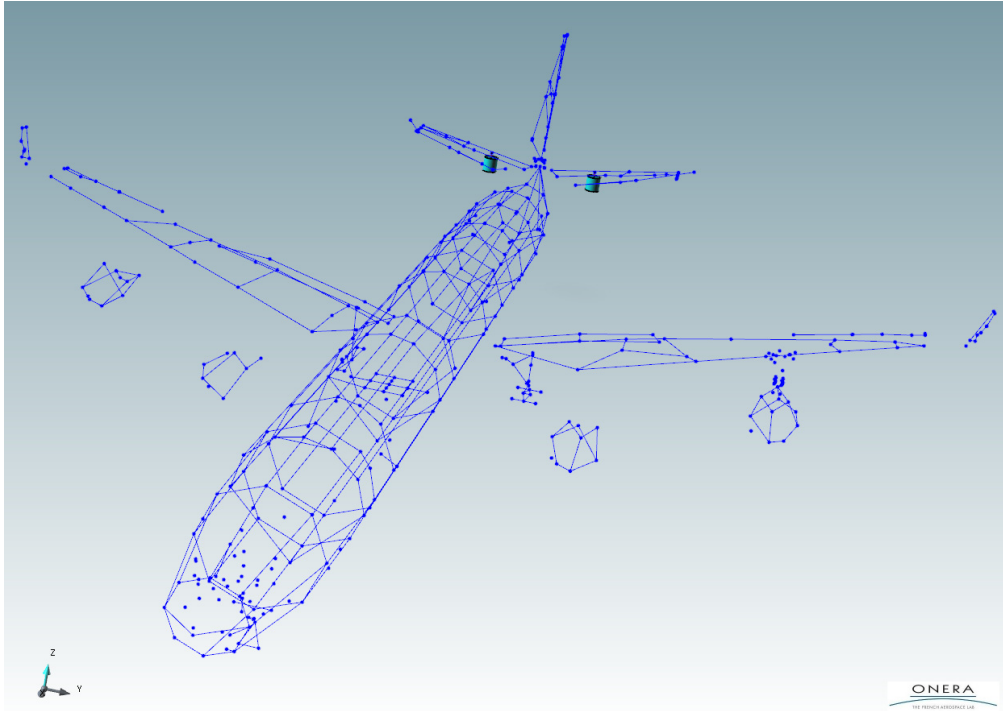


Figure 13: Location of the exciters on the A/C - Excitation on both elevators in Z

Figure 14 shows the combination of sine sweeps applied. On the left elevator, a sweep up superposed to a sweep down between f_1 and f_2 was applied. On the right elevator, the same combination was applied excepting that the sweep down was dephased (180°) to voluntarily uncorrelate the signals. A time delay for the start up of the sweep down was applied to adjust the frequency crossing value to be sure that it will correspond to an area where there's no structural mode.

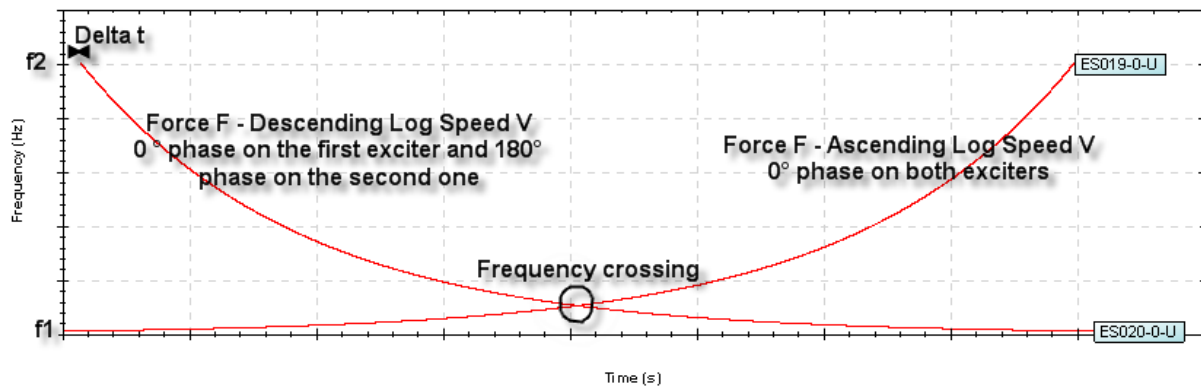


Figure 14: Sweep sine combination to cover frequency range f_1 - f_2 with one sweep up and one sweep down

As we were dealing with uncorrelated excitations, a first standard MIMO processing has been performed to compute the FRFs. These results have been compared to the ones obtained with a SVD processing of each individual sweep (figure 15). We have good results and we can distinguish (on the green and blue curves) the symmetric and anti-symmetric structural modes.

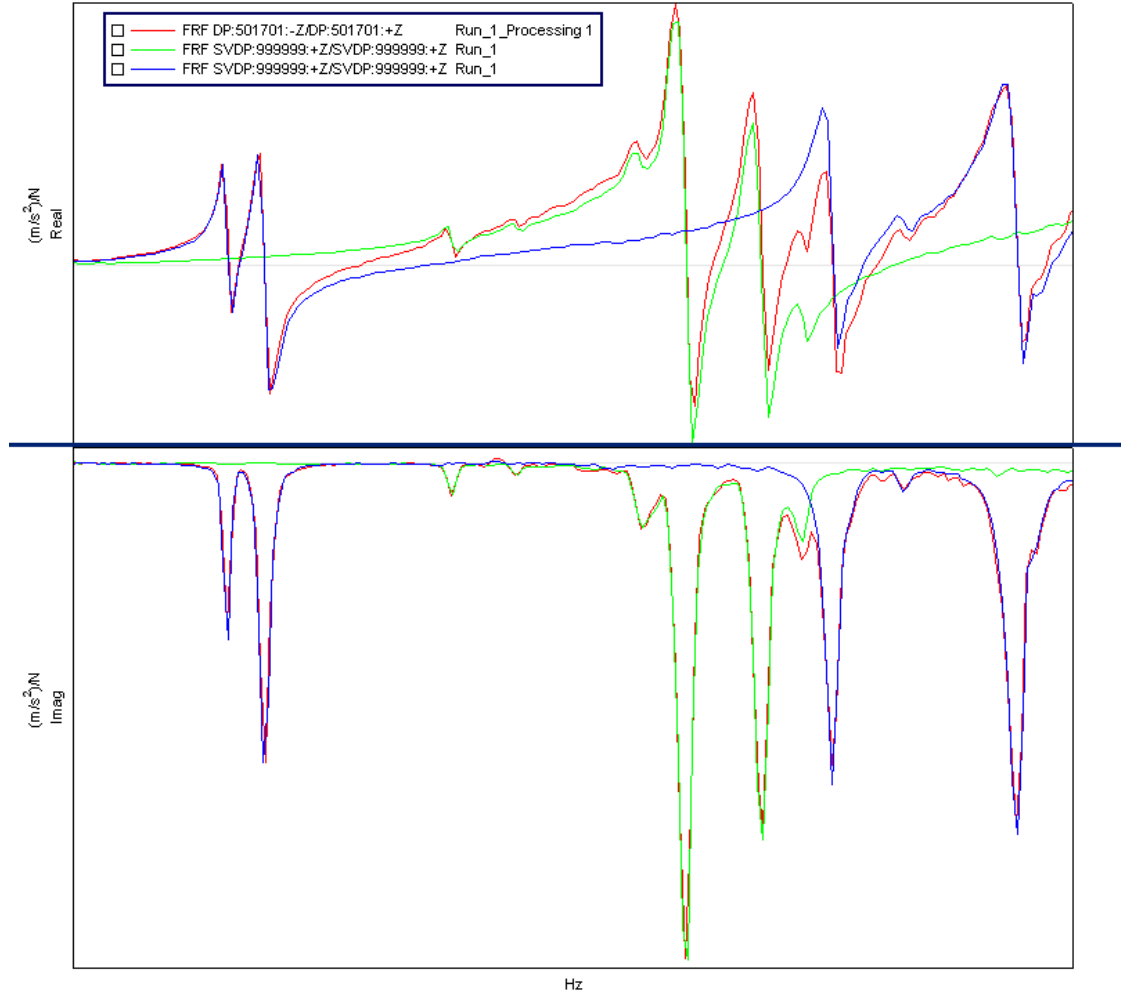


Figure 15: Comparison of the FRFs of the virtual driving point for each individual sweep sine of the combination (in green and blue) and the FRF of one driving point of the combined signal (in red)

One run is enough to excite symmetrical and anti-symmetrical structural modes. We are using uncorrelated excitation signals, so the “classic” MIMO processing for FRFs computing gives good results. In comparison with a random excitation, we are controlling in a better way the energy applied at each frequency. SVDP processing, even if it gives useful extra information, is not necessary to post-process the data.

One disadvantage is that we need a first set of information to setup correctly the frequency crossing value.

The only limitation still comes from the exciters limits, in term of maximum force (F_{max}) and maximum coil course, which cannot be exceeded. The total force applied ($2 \times F$) cannot exceed F_{max} .

4 LOW CREST PERIODIC RANDOM

It was mentioned above that swept sine excitation requires a priori knowledge of the dynamic behaviour of the structure to avoid damage to vibration exciters or test structure. Furthermore, it is known that non-linear effects in structures very often depend on the harmonic vibration amplitude level. Consequently, they are clearly visible in FRFs obtained with swept sine testing e.g. as resonance peak distortions.

The non-linear distortions that are visible in FRFs from swept sine excitation can make the experimental modal analysis difficult. It is shown e.g. in ref. [4] that only a few modes may show non-linear distortions but that modern modal parameter estimators identify multiple stable poles at a single resonance peak. Therefore, the results of experimental modal analysis may suffer from resonance peak distortion.

One of the advantages of random excitation is that no steady harmonic vibration occurs. Consequently, non-linear effects are not clearly visible in the FRFs. Depending on the objective of the test campaign; this can either be an advantage or a disadvantage. For example, if the objective of test campaign is the identification of the modal parameters of an underlying linear structure it is certainly easier to perform modal analysis on FRFs obtained with random excitation. During the FRF measurements, the structure is steadily vibrating but without excessive response amplitudes at resonances of certain mode shapes. A large number of averages is typically used to process the FRFs that do not show any indication of response peak distortion due to non-linearity and are therefore easier to process with experimental modal analysis.

Of course, there are major disadvantages of using random excitation force signals and the most profound ones are mentioned below:

1. the whole excitation energy is spread over the full frequency range
2. random signals as available from modern signal generators typically have a high crest factor
3. random signals are really transient in a sense that they have a continuous spectrum

The approach of using low crest periodic random signals is a way to combine all the advantages of random testing and to improve the specific disadvantages. First of all, it is not necessary that the excitation force signals have continuous spectra. When the frequency range and more importantly the frequency resolution required for the measurement of frequency response functions is known a priori it is possible to use periodic random signals that have a discrete spectrum. Periodic random signals can be generated in such a way that only a discrete number of equally spaced spectral lines are excited that are mandatory for the generation of the frequency response function. By proceeding this way, the excitation energy is more focused and not completely spread over the measurement bandwidth. The crest factor is the ratio of the peak value of a signal to its RMS value. In case of harmonic signals the crest factor is square root of 2. The crest factor of random signals provided by modern signal generators is between 3.5 to 4. It can be optimized in an iterative way by using a clipping algorithm, see e.g. ref [5]. In fact, square root of 2 is the theoretical limit for the crest factor when using a clipping algorithm. Nonetheless, it is possible to generate crest optimized periodic random signals with a crest factor of about 1.6 within 30 iterations of the clipping algorithm. This crest optimization helps to avoid excessive force shocks in the excitation equipment when using this type of excitation signal.

Crest optimized random signals can be implemented as periodic random signals or as true random signals. In case of periodic random signals, only one block of random signal is generated, processed through a clipping algorithm to improve the crest factor, and afterwards a long excitation signal is generated by copying the crest optimized signal block a number of times to achieve a long measurement that allows to improve the measurement quality by an averaging procedure. It is important to note that the length of the one block determines the frequency resolution, or respectively, the spectral lines that will be excited by the periodic

random signal. Thanks to the periodicity of the signal, it is possible to perform averaging directly in the time domain. The averaging is performed without overlap and the resulting averaged time block can be Fourier transformed without window function to avoid leakage. These are optimal conditions for discrete Fourier transformation. However, if the total measurement time is long enough so that enough averages can be processed it is possible to use the standard way of averaging, i.e. overlapping time frames with Hanning window weighting.

When a true crest optimized random signal is used, i.e. a non-periodic random signal, it must be noted that the typical signal processing of random excitation must be applied for Fourier transformation. This means, e.g. averaging with overlapping time frames, Hanning window weighting to reduce leakage, etc. Averaging in the time domain is no longer possible.

Multi point excitation is a very important aspect in testing large structures. It should be noted that the periodic random signals are no longer uncorrelated. During the research GVT campaign, multi-point periodic random excitation has been applied with 2 shakers. In order to get a meaningful estimate for the frequency response function it is necessary to combine the data of excitation runs with independent force patterns. This can be achieved e.g. by applying crest optimized periodic random signals in a symmetric/anti-symmetric way so that the resulting FRFs can be obtained either with the SVDP method or with the classical way of estimating FRFs from multi-point correlated excitation.

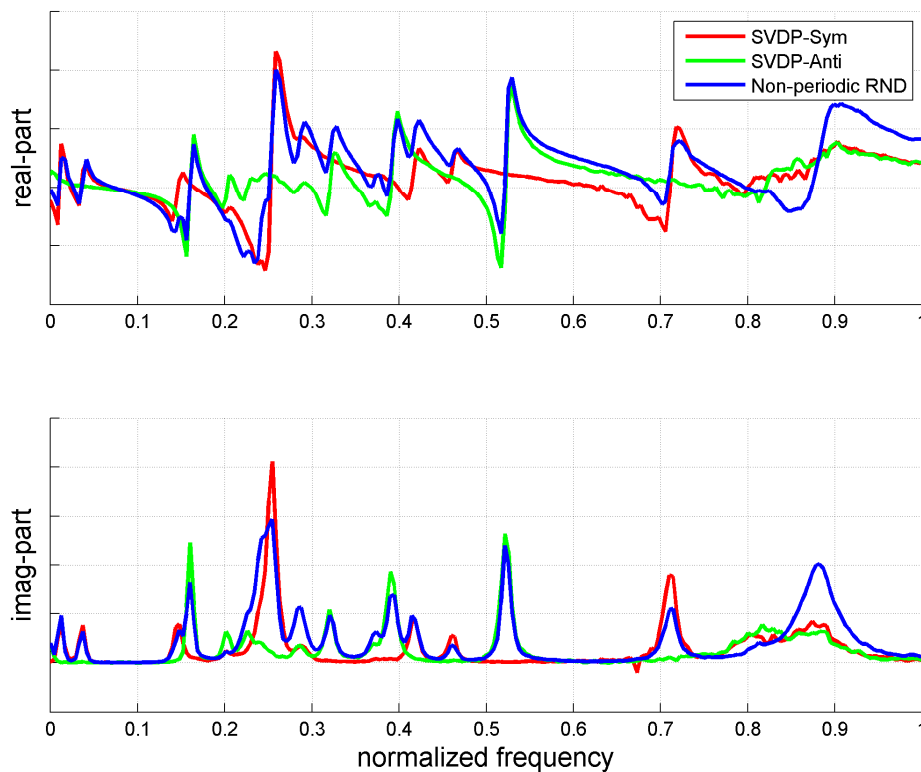


Figure 16: Driving point FRFs obtained with crest optimized periodic random excitation with SVDP for symmetric (red) and anti-symmetric (green) excitation and with uncorrelated non-periodic random (blue)

In figure 16, some illustrative examples are shown for driving point FRFs that have been measured with different approaches of crest optimized random signals. In a first approach, crest optimized periodic random signals have been used. In order to get a meaningful estimate of the FRFs it is either necessary to combine 2 independent measurement runs or to process

FRFs using the concept of single virtual driving points. The red curve in figure 16 shows the resulting FRFs from SVDP applied to a symmetric excitation run with 2 identical crest optimized periodic random signals. The resonance peaks of the symmetric modes should be clearly visible in the respective FRFs. The green curve in figure 16 shows the resulting FRFs from SVDP applied to an anti-symmetric excitation run with 2 identical crest optimized periodic random signals but with opposite sign. The resonance peaks of the anti-symmetric modes should be clearly visible in the respective FRFs. The blue curve in figure 16 shows the driving point FRF that was processed with non-periodic crest-optimized random signals. In this case, 2 uncorrelated random signals that are non-periodic have been used. This is very close to standard random excitation but with optimized crest factors.

5 CONCLUSIONS

These new types of excitation signals complete our toolbox of more “classic” excitation signals for PSM and give us more flexibility and capabilities to address GVT requirements.

It has shown that their usage offers a real gain in productivity, with a good propensity to exhibit non linearities. The quality of the results obtained through dedicated post-processing (SVDP processing typically) is also very convincing.

When the objective of a test campaign does not include the identification of non-linear effects, crest optimized periodic random signals are a good choice to excite a broad frequency range. These excitation signals combine the advantages of random signals with improvements in the distribution of excitation energy over the measured frequency band and the possibility to perform averaging in the time domain and discrete Fourier transformation without application of window functions.

6 REFERENCES

- [1] Füllekrug U., Böswald M., Göge D. and Govers Y (2008). *Measurement of FRFs and Modal Identification in Case of Correlated Multi-Point Excitation*. Shock and Vibration, **15**(3): p. 435-445.
- [2] Alvin K.F., Robertson A.N., Reich G.W., Park K.C (2003). *Structural system identification: from reality to modes*, Computers and Structures, 81, pp. 1149–1176.
- [3] Gloth G., Lubrina P. (2005), *Ground Vibration Testing of the Airbus A380-800*, Proc. of the International Forum on Aeroelasticity and Structural Dynamics IFASD 2005, Munich, Germany
- [4] Böswald M., Göge D., Füllekrug U., Govers Y. (2006). *A Review of Experimental Modal Analysis Methods with respect to their Applicability to Test Data of Large Aircraft Structures*, Proc. of the International Conference on Noise and Vibration Engineering ISMA 2006, Leuven, Belgium,.
- [5] Pintelon R., Schoukens J. (2001). *System Identification – A Frequency Domain Approach*, IEEE Press,